

Elliptic flow phenomenon at ATLAS

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Abstract

We summarize measurements of elliptic flow and higher order flow harmonics performed by the ATLAS experiment at the LHC. Results on event-averaged flow measurements and event-plane correlations in Pb+Pb collisions are discussed along with the event-by-event flow measurements. Further, we summarize results on flow in p +Pb collisions.

1 Introduction

Heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) create hot and dense matter that is composed of deconfined quarks and gluons. A useful tool to study properties of this matter is the azimuthal anisotropy of particle emission. At low transverse momenta ($p_T \lesssim 3 - 4$ GeV), this anisotropy results from a pressure driven anisotropic expansion of the created matter, with more particles emitted in the direction of the largest pressure gradient¹. At higher p_T this anisotropy is understood to result from the path-length dependent energy loss of jets as they traverse the matter, with more particles emitted in the direction of smallest path-length². These directions of maximum emission are strongly correlated, and the observed azimuthal anisotropy can be expressed³ as a Fourier series in azimuthal angle ϕ ,

$$\frac{1}{2\pi p_T} \frac{d^3N}{d\phi dp_T d\eta} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T d\eta} \left(1 + \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos n(\phi - \Phi_n) \right), \quad (1)$$

where η is pseudorapidity, v_n and Φ_n represent the magnitude and direction of the n^{th} -order harmonic, respectively. The n^{th} -order harmonic has n -fold periodicity in azimuth, and the coefficients at low p_T are often given descriptive names, such as “direct flow” (v_1), “elliptic flow” (v_2), or “triangular flow” (v_3).

In typical non-central^a heavy ion collisions, the large and dominating v_2 is associated mainly with the almond shape of the nuclear overlap. However, v_2 in central (head-on) collisions and the other v_n coefficients in general are related to various shape components of the initial state arising from fluctuations of the nucleon positions in the overlap region⁴.

The event-averaged measurement of elliptic flow and higher order harmonics in Pb+Pb collisions is summarized in Sec. 2. The event-by-event flow measurements in Pb+Pb collisions are discussed in Sec. 3. Section 4 summarizes results from two-particle correlations and flow in p +Pb collisions. Measurements in Pb+Pb collisions use the data at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with integrated luminosity of $7 \mu\text{b}^{-1}$. Measurements in p +Pb collisions use the data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with integrated luminosity of approximately $1 \mu\text{b}^{-1}$.

^aIn Pb+Pb collisions, the centrality is estimated using energy deposited in forward ($3.1 < |\eta| < 4.9$) calorimeters.

2 Elliptic flow and higher order harmonics in Pb+Pb collisions

The elliptic flow and higher order harmonics in Pb+Pb collisions were extracted from “event-plane method”^{5,6} and using multi-particle azimuthal correlations^{7,6}. The event-plane method correlates individual tracks with the event-plane direction Φ_n measured using energy deposited in the forward calorimeters. The Fourier coefficient v_n can be expressed as

$$v_n \equiv \langle \cos[n(\phi - \Phi_n)] \rangle, \quad (2)$$

where angle brackets denote two-step averaging, first over charged particles in an event, and then over events.

Significant v_2 – v_6 values were observed as a function of transverse momentum ($0.5 < p_T < 20$ GeV), pseudorapidity ($|\eta| < 2.5$), and centrality. All flow harmonics exhibit similar dependence on p_T . The values of v_n first grow with increasing p_T achieving a maximum at around 3 GeV, then they decrease staying non-zero across the whole measured p_T interval. The p_T dependence of v_n values for $n \geq 3$ is found to follow an approximate scaling relation, $v_n^{1/n}(p_T) \sim v_2^{1/2}(p_T)$, except in the top 5% most central collisions. The values of v_n for $n \geq 2$ do not exhibit a significant variation when evaluated as a function of η . While a similar p_T dependence of flow was previously observed at RHIC, the η dependence of flow at RHIC was different, achieving a maximum at mid-rapidity and decreasing with increasing η ⁸.

The centrality dependence of v_2 reflects the geometry of the collision. It achieves the maximum in mid-central collisions where the ellipticity of the initial overlapping region is largest. The v_2 decreases in more central collisions due to decreasing initial eccentricity and it also decreases in more peripheral collisions due to lack of collectivity⁹. Contrary to the behavior of v_2 , the v_n values for $n \geq 3$ are found to vary only weakly with centrality.

The basic conclusions derived from results obtained using the event-plane method are consistent with the conclusions from results obtained using multi-particle azimuthal correlations. In the event-plane method, only two-particle correlations are exploited in the determination of v_n (see Eq.2). This leads to a well-known problem of disentangling all-particle flow and contributions from particle correlations unrelated to the initial geometry, known as non-flow correlations. These non-flow effects include correlations due to energy and momentum conservation, resonance decays, quantum interference phenomena, and jet production. In order to suppress non-flow correlations, methods that use genuine multi-particle correlations can be employed. Two particle correlations allows to determine Fourier coefficient v_n without estimating the event-plane direction as follows

$$\langle \text{corr}_n\{2\} \rangle \equiv \langle \exp[in(\phi_1 - \phi_2)] \rangle = \langle \cos[n(\phi_1 - \phi_2)] \rangle = v_n\{2\}^2, \quad (3)$$

where ϕ_1 and ϕ_2 denote azimuthal angles of two particles forming a pair. Angle brackets denote two-step averaging, same as in the case of determining the v_n coefficients using the event-plane method. This can be generalized to $2k$ -particle correlations defined as

$$\langle \text{corr}_n\{2k\} \rangle = \langle \exp[in(\phi_1 + \dots - \phi_{1+k} - \dots - \phi_{2k})] \rangle = v_n\{2k\}^{2k}. \quad (4)$$

The multi-particle correlations $\langle \text{corr}_n\{2k\} \rangle$ account for the collective anisotropic flow as well as for the non-flow effects. The anisotropic flow related to the initial geometry is a global, collective effect involving correlations between all outgoing particles. Thus, in absence of non-flow effects, $v_n\{2k\}$ is expected to be independent of k . On the contrary, most of the non-flow effects are contributing to correlations of few particles only. Thus, $2k$ -particle “cumulants” can be used to suppress the non-flow contribution by eliminating the correlations between fewer than $2k$ particles. An example is the cumulant of the four-particle correlations, $c_n\{4\} \equiv \text{corr}_n\{4\} - 2\text{corr}_n\{2\}^2$, which measures the genuine four-particle correlations. If the non-flow contribution is only due to the two-particle correlations, then they are eliminated and $c_n\{4\}$ directly measures flow harmonics. In practice, multi-particle azimuthal correlations are calculated using the generating functions formalism¹⁰.

The cumulant approach to measure flow harmonics also provides a possibility to study elliptic flow fluctuations which can be related to the fluctuations in the initial geometry of the interaction region¹¹. The prediction for the event-by-event variation in the initial geometry obtained from the Glauber Monte Carlo model¹², shows a similar size of fluctuations, suggesting that the elliptic flow fluctuations could originate from fluctuations in the initial geometry.

3 Event-by-event measurement of flow

The flow signal is clearly visible on the event-by-event basis in Pb+Pb collisions. Yield of particles in one event evaluated as a function of azimuthal angle can vary by as much as a factor of three¹³. Measurement of event-by-event flow coefficients allows to directly access the flow fluctuations and thus to better understand the role of initial geometry in forming the flow effects. The event-by-event flow can be quantified by the per-particle “flow-vector”, $\vec{v}_n = (v_n \cos n\Phi_n, v_n \sin n\Phi_n)$. If fluctuations of \vec{v}_n relative to the flow vector associated with the average geometry in the reaction plane^b (RP), \vec{v}_n^{RP} , are described by a two dimensional (2D) Gaussian function in the transverse plane,¹⁴ then the probability density of \vec{v}_n can be expressed as

$$p(\vec{v}_n) = \frac{1}{2\pi\delta_{v_n}^2} e^{-(\vec{v}_n - \vec{v}_n^{\text{RP}})^2 / (2\delta_{v_n}^2)}. \quad (5)$$

The relation between the event-averaged flow coefficients $\langle v_n \rangle$ discussed in Sec. 2 and event-by-event flow coefficients v_n can be then written¹³ as $(v_n^{\text{RP}})^2 \approx \langle v_n \rangle^2 - \delta_{v_n}^2$.

The flow coefficients v_n were measured for $n = 2, 3$, and 4 over the pseudorapidity range $|\eta| < 2.5$ and the transverse momentum range $p_T > 0.5$ GeV¹³. In the very central, 0–2%, collisions, where the eccentricity of the initial overlapping region approaches zero, the measured v_2 distributions are found to approach that of a radial projection of a 2D Gaussian distribution centered around zero ($v_2^{\text{RP}} = 0$). This is consistent with a scenario where fluctuations are the primary contribution to the overall shape for these most central collisions. Starting with the centrality interval 5–10%, the v_2 distributions differ significantly from this scenario, suggesting that they have a significant component associated with the average collision geometry. In contrast, the v_3 and v_4 are consistent with a pure 2D Gaussian-fluctuation scenario (i.e. $v_n^{\text{RP}} = 0$) over most of the measured centrality range. However, a systematic deviation from this fluctuation-only scenario is observed for v_3 and v_4 in mid-central collisions.

The v_n distributions were also measured separately for charge particles with $0.5 < p_T < 1$ GeV and $p_T > 1$ GeV. The shape of the unfolded distributions, when rescaled to the same $\langle v_n \rangle$, is found to be nearly the same for the two p_T ranges. This suggests that the hydrodynamic response to the eccentricity of the initial geometry has little variation in this p_T region. The conclusions were quantified in more details e.g. by evaluating the ratios of width to the mean of measured v_n distributions. Further, the measured v_n distributions were compared with the eccentricity distributions of the initial geometry from the Glauber model¹⁵ and MC-KLN model¹⁶. Both models were found to fail in describing the data consistently over most of the measured centrality range.

More insight to the role of fluctuations in flow effects can be also gained by measuring the event-plane correlations. If the fluctuations in initial geometry are small and random, the orientations of event-plane directions Φ_n of different order are expected to be uncorrelated. Fourteen correlators of event-plane directions were measured¹⁷ using a standard event-plane method and a scalar-product method¹⁸. Several different trends in the centrality dependence of these correlators were observed. These trends were not reproduced by predictions based on the Glauber model, which includes only the correlations from the collision geometry in the initial state. Calculations that include the final state collective dynamics are able to describe qualitatively, and in some cases also quantitatively, the centrality dependence of the measured correlators. In particular, the AMPT model¹⁹ which generates collective flow by elastic scatterings in the partonic and hadronic phase was shown to reproduce the trends seen in the data. These observations suggest that both the fluctuations in the initial geometry and non-linear mixing between different harmonics in the final state are important for creating the correlations in the momentum space.

4 Flow in p+Pb collisions

High-multiplicity p+Pb events provide a rich environment for studying observables associated with high parton densities in hadronic collisions. Tool to probe this physics is the two-particle

^bReaction plane is defined by the impact parameter vector and the beam axis. Reaction plane needs to be distinguished from the event plane Φ_n which is directly accessible event-by-event.

correlation function measured in terms of the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of selected particle pairs, $C(\Delta\eta, \Delta\phi)$. The first studies of two-particle correlations in the highest-multiplicity $p+p$ collisions at the LHC²⁰ showed an enhanced production of pairs of particles at $\Delta\phi \sim 0$, with the correlation extending over a wide range in $\Delta\eta$, a feature frequently referred to as a “ridge.”

Similar long range ($2 < |\Delta\eta| < 5$) correlations were observed in $p+\text{Pb}$ collisions on the near-side ($\Delta\phi \sim 0$) exhibiting a rapid grow with increasing event activity characterized by the transverse energy (E_T^{Pb}) summed over $3.1 < \eta < 4.9$ in the direction of the Pb beam. Further, a long-range away-side ($\Delta\phi \sim \pi$) correlation was found to be present in high-event activity $p+\text{Pb}$ collisions after subtracting the expected contributions from recoiling dijets and other sources estimated using events with small E_T^{Pb} ²¹. In this measurement, the correlation function $C(\Delta\eta, \Delta\phi)$ was also projected to the $\Delta\phi$ direction. The resultant $\Delta\phi$ correlation was found to be approximately symmetric about $\pi/2$ exhibiting thus a clear flow signal. To quantify the size of the flow signal, v_2 is determined using two- and four-particle cumulants²². A significant magnitude of v_2 is observed for both $v_2\{2\}$ and $v_2\{4\}$, although $v_2\{2\}$ is consistently larger than $v_2\{4\}$, indicating a sizable contribution of non-flow correlations to $v_2\{2\}$. The transverse momentum dependence of $v_2\{4\}$ shows a behavior similar to that measured in Pb+Pb collisions.

Presence of flow in $p+\text{Pb}$ collisions might have not been expected due to the small size of the produced system compared to the mean free path of interacting constituents. Despite that, it was observed that the prediction of viscous hydrodynamics can reproduce the magnitude of the measured flow when configured with similar initial conditions as those used for Pb+Pb collisions^{22,23}. Many of the physics mechanisms proposed to explain the $p+p$ ridge, including multi-parton interactions, parton saturation, and collective expansion of the final state, are also expected to be relevant in $p+\text{Pb}$ collisions and they may contribute to the observed flow. The flow phenomenon in $p+\text{Pb}$ collisions thus clearly deserves more investigations to understand its origin.

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